linear - Floats!!

small aperture - lower resolution & vice versa

gamma corrected - ints ok

blurring that eye does is in energy domain

data processing done in units that are linear in energy - USE FLOATS

no single coordinates good for all tasks (linear vs gamma corrected)

↳ same for color spaces

Opponent Color Spaces

- Perception of color is usually not best represented in RGB.
- A better model of HVS is the so-call opponent color model
- Opponent color space has three components:
  - O_1 is luminance component - usually Y of XYZ
  - O_2 is the red-green channel

$$O_2 = G - R$$

  - O_3 is the blue-yellow channel

$$O_3 = B - Y = B - (R + G)$$

- Comments:
  - People don't perceive redish-greens, or bluish-yellows.
  - As we discussed, O_1 has a bandpass CSF.
  - O_2 and O_3 have low pass CSF's with lower frequency cut-off.

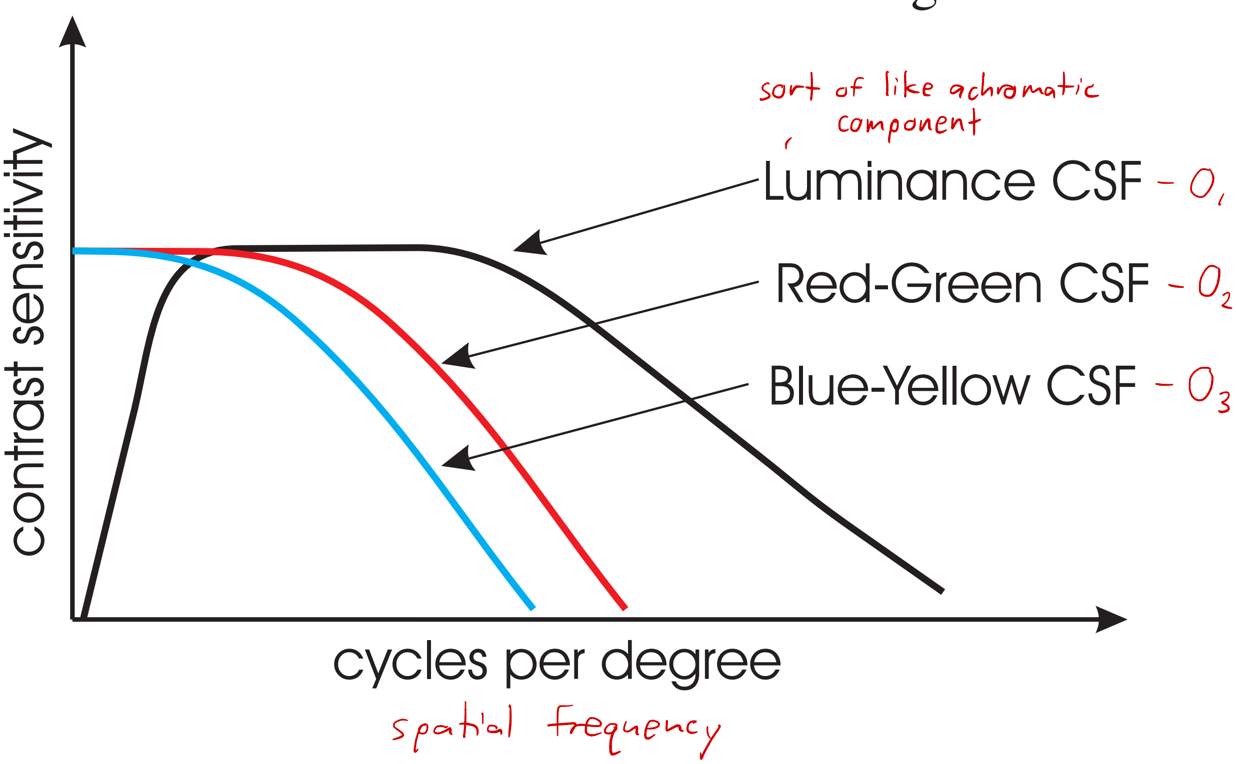
Spatial Frequency Response of Visual System

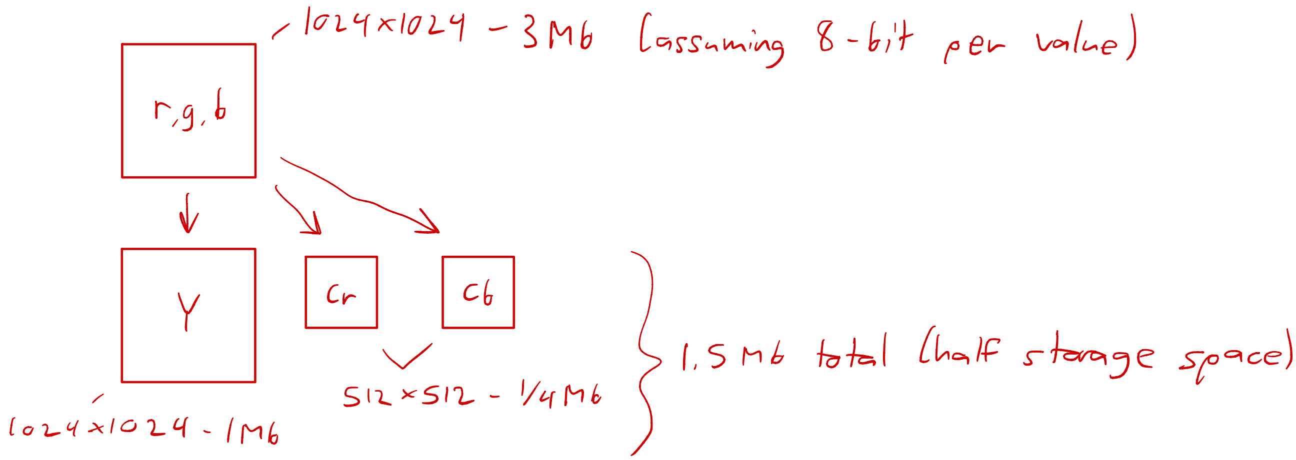
Opponent Channel Contrast Sensitivity Functions (CSF)

color coordinates that decouple the frequency response is NOT rgb

- Typical CSF functions looks like the following.

spatial frequency response





"The world is understandable"

FLOPS

- number of operations/ multiplies, etc

"Computers aren't that unknowing"

- recognize importantce, can always figure things out

↳ is my program running correctly?

Consequences of Opponent Channel CSF

- Luminance channel is
  - Bandpass function
  - Wide band width ⇒ high spatial resolution.
  - Low frequency cut-off ⇒ insensitive to average luminance level.
- Chrominance channels are
  - Lowpass function
  - Lower band width ⇒ low spatial resolution.
  - Low pass ⇒ sensitive to absolute chromaticity (hue and saturation).

Some Practical Consequences of Opponent Color Spaces

- Analog video has less bandwidth in I and Q channels.
- Chrominance components are typically subsampled 2-to-1 in image compression applications.
- Black text on white paper is easy to read. (couples to O_1)
- Yellow text on white paper is difficult to read. (couples to O_3)
- Blue text on black background is difficult to read. (couples to O_3)
- Color variations that do not change O_1 are called "isoluminant".
- Hue refers to angle of color vector in (O_2, O_3) space.
- Saturation refers to magnitude of color vector in (O_2, O_3) space.

Opponent Color Space of Wandell

- First define the LMS color system which is approximately given by

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.3910 & 1.1650 & 0.0870 \\ 0.0100 & -0.0080 & 0.5630 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- The opponent color space transform is then[1]

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -0.59 & 0.80 & -0.12 \\ -0.34 & -0.11 & 0.93 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

- We many use these two transforms together with the transform from sRGB to XYZ to compute the following transform.

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 0.2814 & 0.6938 & 0.0638 \\ -0.0971 & 0.1458 & -0.0250 \\ -0.0930 & -0.2529 & 0.4665 \end{bmatrix} \begin{bmatrix} sR \\ sG \\ sB \end{bmatrix}$$

- Comments:
  - O_1 is luminance component
  - O_2 is referred to as the red-green channel (G-R)
  - O_3 is referred to as the blue-yellow channel (B-Y)
  - Also see the work of Mullen '85[2] and associated color transforms.[3]

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[1] B. A. Wandell, *Foundations of Vision*, Sinauer Associates, Inc., Sunderland MA, 1995.

[2] K. T. Mullen, "The contrast sensitivity of human color vision to red-green and blue-yellow chromatic gratings," *J. Physiol.*, vol. 359, pp. 381-400, 1985.

[3] B. W. Kolpatzik and C. A. Bouman, "Optimized Error Diffusion for Image Display," *Journal of Electronic Imaging,* vol. 1, no. 3, pp. 277-292, July 1992.

Paradox?

- Why is blue text on yellow paper easy to read??
- Shouldn't this be hard to read since it stimulates the yellow-blue color channel?

A: Blue & Yellow are <u>not</u> isoluminant

↳ therefore blue text on yellow paper simulates the illuminance chanel

Blue on black also bad

Yellow on white background is bad, as they are relatively isoluminant

$\boxed{M}$ $\boxed{M^{-1}}$

Better Understanding Opponent Color Spaces

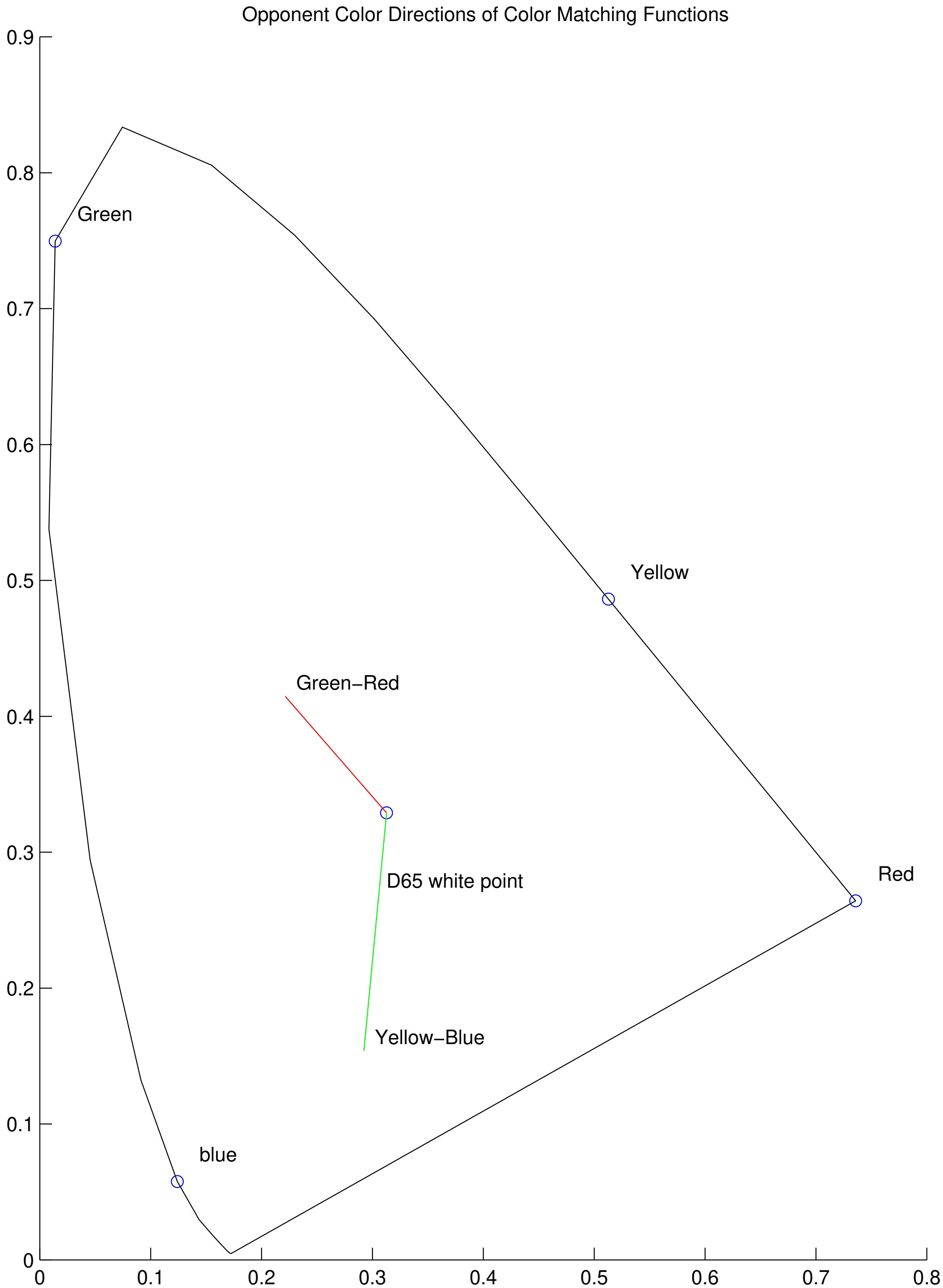
- The XYZ to opponent color transformation is:

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$= \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- What are v_y, v_{gr}, and v_{by}?
  - They are row vectors in the XYZ color space.
  - v_{gr} is a vector point from red to green
  - v_{by} is a vector point from yellow to blue
  - They are not orthogonal!

Plots of v_y, v_{gr}, and v_{by}



Answer to Paradox

- Since v_y, v_{gr}, and v_{by} are not orthogonal

$$\begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \left[v_y^t \, v_{gr}^t \, v_{by}^t \right] \neq \text{identity matrix}$$

- Blue text on yellow background produces and stimulus in the v_{by} space.

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} v_{by}^t = \begin{bmatrix} -0.3958 \\ -0.1539 \\ 0.4627 \end{bmatrix}$$

- This stimulus is not isoluminant!
- Blue is much darker than yellow.

Basis Vectors for Opponent Color Spaces

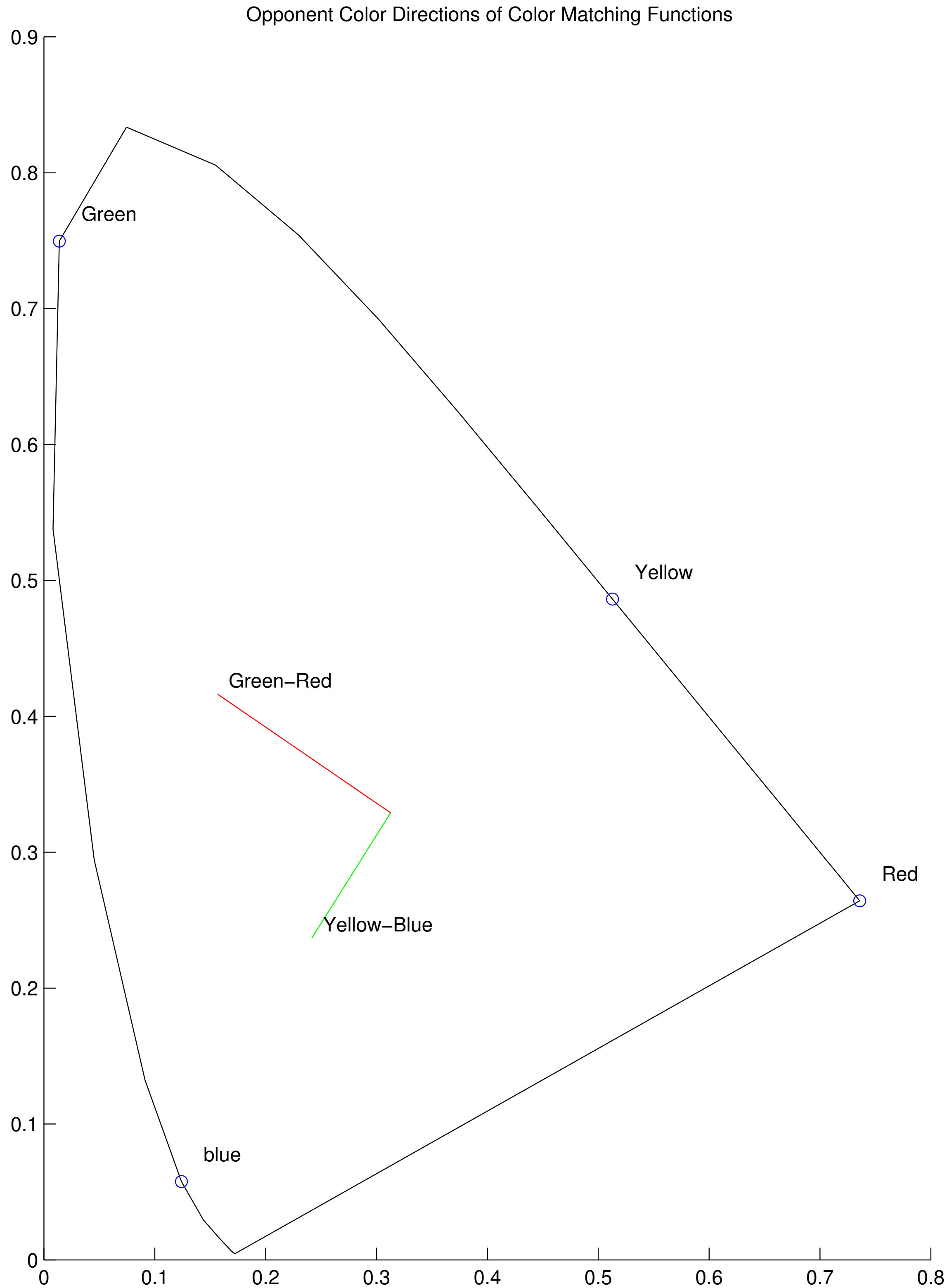
- The transformation from opponent color space to XYZ is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.9341 & -1.7013 & 0.1677 \\ 0.9450 & 0.4986 & 0.0522 \\ 0.8157 & 0.3047 & 1.9422 \end{bmatrix} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix}$$

$$= [c_y \, c_{gr} \, c_{by}] \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix}$$

- What are c_y, c_{gr}, and c_{by}?
  - They are column vectors in XYZ space.
  - c_{gr} is a vector which has no luminance component.
  - c_{by} is a vector which has no luminance component.
  - They are orthogonal to the vectors v_y, v_{gr}, and v_{by}.

Plots of c_y, c_{gr}, and c_{by}



Interpretation of Basis Vectors

- Since c_y, c_{gr}, and c_{by} are orthogonal to v_y, v_{gr}, and v_{by}, we have

$$\begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \left[c_y \; c_{gr} \; c_{by} \right] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Therefore, we have that

$$\begin{aligned} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} &= \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} c_{by} \\ &= \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} 0.1677 \\ 0.0522 \\ 1.9422 \end{bmatrix} \\ &= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{aligned}$$

- So, c_{by} is an isoluminant color variation.
- Something like a bright saturated blue on a dark red.

Solution to Paradox

- Why is blue text on yellow paper is easy to read??
- Solution:
  - The blue-yellow combination generates the input v_{by}.
  - This input vector stimulates all three opponent channels because it is not orthogonal to c_y, c_{gr}, and c_{by}.
  - In particular, it strongly stimulates c_y because it is **not** iso-luminant.